Military Load Carriage: A Novel Method of Interface Pressure Analysis

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Summary

In the current military climate there is a constant need to strike a balance between the increasing amount of equipment carried by the modern soldier and the need to optimise performance and health. In co-operation with the Defence Clothing and Textile Agency, load carriage equipment has been developed making use of novel interface materials. These are used to distribute interface contact areas more extensively yet maintain air space next to the body surface. The purpose is to minimise peak pressure zones and reduce discomfort and pain so as to optimise performance and reduce the opportunity for injury. The paper will present novel methods for analysing interface pressures measured during load carriage on a treadmill and will consider the efficacy of this brief, evaluative technique.

Introduction

Throughout history man has been dependent upon the manual carriage of loads for purposes of survival, migration and warfare. Although modern technologies have managed to liberate him from this in many situations, there are still many occupational tasks, which require the carriage of heavy loads over long time periods. Foot soldiers are often required to carry heavy loads over much longer distances than any civilian counterpart. As the loads carried by soldiers have risen considerably over time so has the amount of research conducted into this area, with the aim of making the foot soldier more effective in terms of how much they can carry and for how long they can carry it.

The majority of the early work carried out in this area has concentrated on the physiological and specifically the cardio-respiratory effects of load carriage and the results of this are well established (Datta and Ramanathan, 1971; Datta et al., 1973; Epstein et al., 1988; Patton et al., 1989; Holewijn, 1990; Lind and McNicol, 1968). More recently however, the emphasis has shifted towards a more ergonomic, user-centred approach and has started to look towards making improvements to reduce the overall strain on the soldier. This work has included attempts to utilise the areas of the body most suited to the carriage of heavy loads with the aim of improving user comfort and health. A large part of the recent work in this area has been carried out by the Ergonomics Research Group at Queens University, who have developed a comprehensive suite of biomechanical tools for evaluating load carriage systems (Doan et al., 1998; Johnson et al., 1998; Rigby et al., 1998). As part of this work, they have been investigating the effects of carried loads on interface pressures and have developed an extension methodology using the Tekscan pressure measurement system (Bryant et al., 1996; Stevenson et al., 1995 and 1996.)

This work has concentrated on the effect of Load Carriage Systems on interface pressure and used only human participants, a method that has not been extensively studied before. The aim of this work was to develop an objective methodology, which, along with participant ratings of comfort, will allow reliable and repeatable comparisons of load carriage systems. New interface materials were evaluated, in terms of their ability to effectively distribute pressure, in order to prevent user pain and discomfort, the precursors to damage, injury and loss of performance.

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The aim of the first experiment was to evaluate an air mesh material which has been found to increase the evaporative heat loss from the body when exercising in a hot climate (Martin and Hooper, 1999). Due to the nature of this material, it may increase pressure distribution and improve user comfort. It was compared directly with the current in-service backpack of the British military, which incorporates 90-pattern foam at the interface.

The aim of experiments 2,3 and 4 was to look at a large number of different designs of shoulder straps in order to examine the effects on comfort and pressure distribution. The designs varied in width and interface material, which included foams, air meshes and plastics. The first goal was to select a smaller number of prototype straps for a further, more comprehensive evaluation involving a much larger sample.
Experiment 5 investigated different designs of backpack belts, their effect on shoulder pressures and overall pressure distribution, different interface materials and body location.

Methods

In total, 38 healthy participants (41 male, 31 female) participated in five experiments under conditions approved by the Ethical Advisory Committee of Loughborough University. The participants had a (mean ± SD) age of 22.35 ± 2.89 years, weight of 68.27 ± 7.5 kg, height of 174.72 ± 7.84 cm, and B.M.I of 22.3 ± 1.5 kg/m^2. Prior to participation participants completed and signed a form of consent.

One military rucksack was used in all the studies. This pack had changeable shoulder straps and hip belts allowing the conditions to be changed whilst keeping the load properties the same. The rucksack was kept at a standard load of 20kg. During the trials, the participants wore training shoes, cotton tracksuit trousers and cotton T-shirt. No participant took part in more than one of the experiments. The rucksacks were donned and fitted to the stipulation of the experimenter, providing consistency of fit. The participants were then permitted to re-adjust the tension to suit their own preferences.

Each trial lasted of 30 minutes treadmill walking at a speed of 3.5km/h whilst carrying the pack under investigation. The trials were held at the same time of day for each participant and the order in which the packs were carried was randomised. All of the trials were separated by at least a week.

Whilst completing the trials, shoulder pressure was measured using the Tekscan™ system. An F-scan sensor was used consisting of 952 individual sensels over the shoulder area. In addition, in experiment 5 interface pressure at the hip area was also measured.

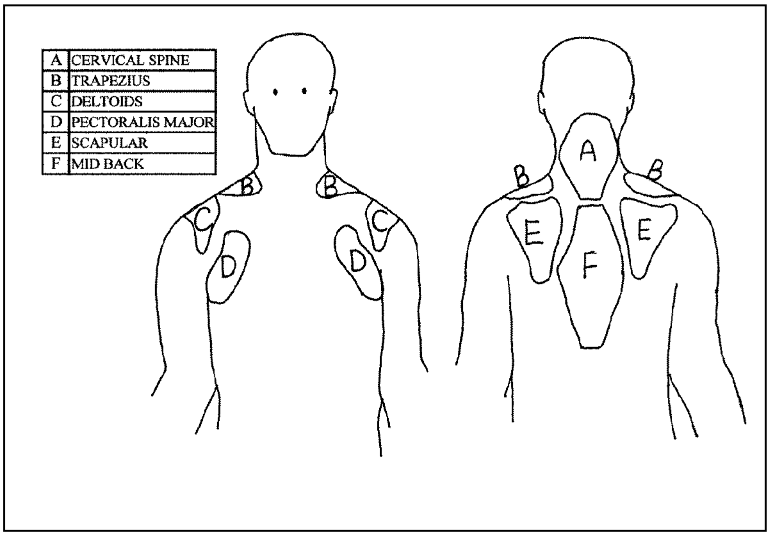
Before the trials, the sensors were equilibrated and calibrated in a pressure bladder. In order to ensure the same placement of the sensors in all conditions the real time monitoring of the Tekscan software was used. One of the individual sensels was matched with a certain anatomical landmark on the participant's body. For example in the case of one of the participants sensel 34, 19 (row, column) was matched up with the superior aspect of the left clavicle, 4cm from the sternal end, and sensel 34, 3 was matched up with the inferior aspect of the clavicle, 14 cm from the sternal end.

Repeatability of the pressure measurements was assessed by a test - re-test study of 5 participants. Each participant attended the lab on two different occasions and was measured carrying the same backpack, which were fitted as detailed above. The same calibration process was used on both occasions but a different sensor was used for each occasion. Out of a total out of 723 individual pressure readings (greater than zero), 92.51% (669) were found to be identical, 5.67% (41) were within 1% of the original reading, 1.67% (12) were within 5% and 0.15% (1) was within 10%.

During the trial, pressure readings were taken at 5-minute intervals, 10 frames over a 0.5-second time period were recorded starting at left heel strike. Prior to experimentation, pressure throughout the gait cycle was examined and this was found to be the point where pressure was the highest. The pressure sensors were split into six zones for the purpose of analysis, participants were asked to rate their comfort underneath the pack at six areas over the shoulder

area as displayed on a body map (figure 1). The scale ranged from 1 - 5, with 1 being 'comfortable' and 5 being 'unbearably uncomfortable'.

Figure 1. Body Map showing the six shoulder zones



Indices of pressure distribution:

Mean overall pressure	Total force exerted on the sensor divided by the number of individual sensing cells
Mean top 120 sensels	The mean of the highest 20 (12%) individual sensing cells in each 'zone' of the sensor.
Maximum pressure	The single highest recorded pressure on the sensor
Contact Area	The area of the sensor with recorded pressure

Paired t-tests and repeated Analysis of Variance tests were used to determine statistical variance in pressure between conditions. The Wilcoxin matched-pairs signed ranks test was used to assess the significance of difference between the ratings of perceived general comfort given by participants. Statistical significance was accepted at the 0.05 level. Reported results are means ± SD.

Results

Experiment 1 – Comparison of an air mesh material at the body interface with the in-service 90 Pattern foam.

The overall pressures underneath the shoulder straps in each condition were not found to be significantly different, as the designs of the pack and mass location were identical with only the interface material differing between the packs. This allowed comparisons between the conditions to be made, as the loads in each case were the same (Table 1).

Table 1. Differences in mean pressure distribution between air mesh pack and standard pack (n= 18)

	Air Mesh Interface	90 Patt. Foam Interface
Overall mean pressure (kPa)	7.08 ± 0.63	6.09 ± 0.44
Mean of top 120 senses (kPa)	19.5 ± 1.57	29.5 ± 1.94 *
maximum pressure (kPa)	78.2 ± 18.0	115.8 ± 29.1 *
Mean comfort rating	3.29 ± 0.72	4.55 ± 0.77 *

* difference significant at p = < 0.05 level

When the pressure distributions are examined however, it can be seen from the highest 120 (12%) individual pressure readings that the air mesh interface reduces the value of these by around a third, from 29.5k Pa to 19.5 kPa. This is also illustrated by the reduced mean maximum pressure of 78.2 kPa compared with 115.8 kPa for the standard interface material. The air mesh pack appears to take the same load and distribute it more evenly over the body surface, resulting in less pressure hot spots. It would appear that participants are sensitive to this change in pressure distribution as they consistently rated the air mesh more comfortable than the standard pack after carrying both for 30 minutes. The average comfort rating was 3.29, between uncomfortable and very uncomfortable, compared with 4.55, between very uncomfortable and unbearably uncomfortable for the standard pack.

Experiment 2 – Comparison of four different 90 pattern foam shoulder straps; standard (A), narrower (B), wider (C) and with plastic insert (D).

Again, the differences in overall shoulder pressures were found to be non-significant (table 2). The means of the highest 12% of sensels were not found to differ significantly when the thickness of the straps were varied, although the narrower 90 pattern strap was found to result in slightly higher readings. The maximum pressures support this, the wider strap does not appear to result in any difference from the standard pack with values very similar to the standard 90 pattern strap, however the narrower strap results in higher pressures.

Table 2. Effect on pressure distribution of 90 pattern foam (n=5)

	Standard	Narrower	Wider	Plastic Ins.
Overall mean pressure (kPa)	4.3 ± 1.2	5.0 ± 0.9	4.8 ± 1.1	5.1 ± 0.9
Mean of top 120 sensels (kPa)	20.4 ± 5.1	25.5 ± 4.1	19.6 ± 5.4	8.2 ± 0.6 *
maximum pressure (kPa)	99.8 ± 5.6	117.8 ± 6.6*	94.2 ± 10.2	78.8 ± 5.3 *
contact area (cm^2)	38.2 ± 8.1	25.4 ± 6.2	31.4 ± 7.8	47.7 ± 4.3 *
Mean comfort rating	3.78 ± 0.6	4.33 ± 0.7*	3.82 ± 0.5	3.55 ± 0.6

* significant difference found between the other three conditions (p = < 0.05 level)

Adding a plastic insert does have an effect on pressure distribution when compared with the identical strap without plastic. The mean of the highest 120 sensels was 8.2kPa, significantly lower than 20.4kPa underneath the standard strap. The maximum pressures are also reduced to a mean of 78.8kPa compared with 99.8kPa. Adding the plastic insert distributes pressure more effectively by increasing the surface area of the body used for pressure distribution, the contact surface area increasing from 38.2cm^2 underneath the standard strap to 47.7cm^2 when the plastic is added. Again, these objective variables are supported by the ratings of the participants, the strap incorporating the plastic insert being rated lower than the standard strap, 3.55 compared with 3.78. The participants rated the wider shoulder strap very similarly to the standard pack, although the narrower strap was rated significantly less comfortable than the other three belts, again backing up the objective data.

Experiment 3 – Comparison of four shoulder straps consisting of three different air Meshes (E, H, and J) and one with mesh J with added plastic (I).

The overall mean pressure exerted on the shoulder in all four conditions was the same (table 3). In this experiment Strap E consisted of the air mesh material found to be effective in aiding evaporative heat loss in hot environments, and also more effective at distributing pressure over the shoulder area (experiment. 1). It can be seen that strap H, which consisted of a different air mesh material, was more effective than the mesh E at distributing pressure: resulting in a lower mean maximum pressure of 71.2 kPa, and a significantly lower mean of the highest 120 pressures (17.8 kPa). Again the mechanism for this appears to be the greater surface area of the shoulder being used for pressure distribution. Strap J, which consisted of another air mesh material, performed very similarly to strap E.

Table 3. Effect on mesh type and plastic insert on pressure distribution (n=5)

	E	H	I	J
Overall mean pressure (kPa)	5.2 ± 1.7	4.9 ± 0.6	5.4 ± 1.2	5.1 ± 0.9
maximum pressure (kPa)	78.2 ± 6.5	71.2 ± 4.4	84.4 ± 9.8	82.4 ± 8.1
Mean of top 120 sensels (kPa)	24.8 ± 4.2	17.8 ± 3.3*	26.3 ± 2.4	25.2 ± 6.7
contact area (cm^2)	25.1 ± 3.2	32.4 ± 7.1*	17.4 ± 4.3*	24.8 ± 6.3
Mean comfort rating	3.2 ± 0.7	3.1 ± 0.4	3.3± 0.5	3.3 ± 0.6

* significant difference found between the other three conditions (p = < 0.05 level)

It would appear that adding a plastic insert to the mesh of strap J, to make strap I, does not result in a further reduction in shoulder pressures. When comparing the pressure indices of straps I and J, it can be seen that adding plastic increases the mean maximum pressures and the mean of the highest 120 sensels cells, although these differences are not statistically significant. This indicates that adding a rigid plastic to an interface material may not always have a beneficial effect on pressure distribution,

Experiment 4 – Comparison of four shoulder straps consisting of three different air Meshes (M, N, and Q) and one with mesh Q with added plastic (O).

All of these meshes performed well with maximum pressures lower than the standard 90-pattern foam. Out of the 3 mesh straps without plastic inserts (M, N and Q) it is Q that performs best with the lowest mean maximum pressure, 58.4 kPa compared with 70.8 kPa for M and 81.8 kPa for N. It also has a high contact area used for pressure distribution, 90.2cm^2 compared with 90.4cm^2 (N) and 77cm^2 (M). The performance in terms of pressure distribution of the mesh used in strap Q is further enhanced when a plastic insert is added (strap O). This plastic insert results in a lower mean maximum pressure (43.8kPa) and a lower mean of the top 12% of pressures (16.6 kPa). Adding plastic increases body contact surface area still further to 96.7 cm2. Out of these 4 straps the participants rated O as the most comfortable, closely followed by Q, 2.78 and 2.99 respectively, although straps M and N were also rated well, 3.0 and 3.2.

Table 4. Effect of mesh type on pressure distribution (n=5)

	Mesh 'M'	Mesh 'N'	Mesh 'O'	Mesh 'Q'
Overall mean pressure (kPa)	4.8 ± 0.9	5.3 ± 1.1	5.4 ± 0.8	5.5 ± 1.0
maximum pressure (kPa)	70.8 ± 19.3	81.8 ± 6.2	43.8 ± 9.0*	58.4 ± 5.2 *
Mean of top 120 sensels (kPa)	20.8 ± 7.1	28.8 ± 6.6	16.6 ± 3.5*	23.2 ± 1.6 *
contact area (cm^2)	77.2 ± 7.1*	90.4 ± 3.7	96.7 ± 8.4	90.2 ± 3.2
Mean comfort rating	3.0 ± 0.9	3.2 ± 0.7	2.8 ± 0.5	3.0 ± 0.5

* significant difference found between the other three conditions (p = < 0.05 level)

Experiment 5 – Influence of backpack belts on shoulder and hip pressures. Comparison of different interface materials and placement, 90 Pattern foam belts at waist and hip level (1 and 2), air mesh shown to have thermal benefits with added plastic (3) and two new air meshes with plastic inserts (4 and 5).

The most important consideration when evaluating the performance of a backpack belt is how effective it is in reducing shoulder pressure. Out of the 5 belts under investigation, belt 1 resulted in the smallest reduction in shoulder pressure, 8.7%. This belt was the current 90-pattern foam belt and was situated around the participant's waist. Belts 2, 3, 4 and 5, which were situated around the hips, reduced shoulder pressure by 48.3%, 42%, 41.4% and 39.2% respectively. It is therefore clear that placement around the hips is a necessity for good displacement of load from the shoulders.

Table 5. Effect of Belt Design on mean pressure distribution at the hips (n=5)

	1	2	3	4	5
%reduction in shoulder pres s.	8.7± 4.2*	48.3 ± 6.2	42 ± 8.3	41.4 ± 12.3	39.2 ± 14.2
Mean overall pressure (kPa)	3.2 ± 1.4	2.9 ± 0.6	4.6 ± 0.4	3.68 ± 1.0	1.7 ± 0.6
maximum pressure (kPa)	139 ± 12.0*	82 ± 8.3	88 ± 14.9	79 ± 5.2	57 ± 17.1*
Mean of top 120 cells (kPa)	25.6 ± 5.7	19.7 ± 5.2	26.9 ± 5.1	27.1 ± 3.7	16.3 ± 2.6
contact area (cm^2)	21.3 ± 3.2	23.1 ± 7.4	25.5 ± 4.5	21.3 ± 3.3	26.8 ± 7.4
comfort rating (shoulder)	2.85 ± 0.8	2.65 ± 0.6	2.58 ± 0.7	2.61 ± 0.4	2.57 ± 0.3
comfort rating (hip)	2.30 ± 0.4	2.22 ± 0.5	2.08 ± 0.6	1.98 ± 0.3	2.13 ± 0.5

* significant difference found between the other three conditions ($p = < 0.05$ level)

There was no significant difference in the reduction of shoulder pressure between the four hip belts. However, a reduction of shoulder pressure results from passing a proportion of the load amplitude or spread to the hips (or waist). A change in the pressure footprint (scale/area or both) under the belt must result. Therefore the issue of how well this pressure is distributed at the hips may be the deciding factor in the choice of a belt. Hip belt 5 results in the lowest mean maximum pressure of 55 kPa and also results in the best shoulder ratings of comfort, 2.57. The small differences in ratings of hip comfort for the four hip belts indicate that the participants are less sensitive to differences in pressure in this area, as is to be expected due to the difference in anatomy of this area when compared with the shoulder area. It may be the case therefore that the choice of an interface material should be based on its ability to reduce shoulder pressure and increase shoulder comfort rather than optimising hip comfort.

Conclusions

Methodological

In conclusion, a reliable and repeatable laboratory tool has been developed, which is sensitive to design differences between load carriage systems, and which produces results which agree with participants ratings of perceived comfort. However, a lot of work has still to be carried out regarding the absolute values of these pressure measurements. This will be required in order to make conclusions regarding acceptable limits at the interface. It should be pointed out that in this paper measurements have been taken at the point in the gait cycle where interface pressure is at its greatest. In addition, the next step of this work is to attempt to modify this tool for use in the field, allowing measurements to be made over different terrain and in different environments.

Design

From this work, a number of recommendations can be made, although final prototype testing and field trials are required to confirm these. Improvements in pressure distribution and user comfort can be achieved by altering the interface material of a backpack. The mechanism is to effectively distribute pressure, thereby

reducing higher pressures, which are likely to lead to discomfort and may eventually lead to pain and loss of function.

One material that has been found to do this is monofillament air mesh, and this also has the benefit of enabling soldiers to lose excess heat. However, other mesh types may improve pressure distribution still further and these need to be investigated in future work. The majority of the meshes investigated in this work perform better than the standard foam currently used as the interface material for British military backpacks.

The use of a plastic insert to an interface material may improve pressure distribution by increasing still the surface area of the body used for pressure distribution, resulting in lower pressures. However, it has been shown that this may not be the case for every interface material and comprehensive work must be undertaken in order to confirm this.

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